L. Inspection of Spot Welds Using an Ultrasonic Phased Array

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Objective

- Develop an ultrasonic phased-array system that is sufficiently fast, accurate, robust in manufacturing environments, and cost-effective to be suitable for on-line inspection of spot welds used in automotive components.

Approach

- Use state-of-the-art ultrasonic phased-array technology to develop a spot-weld inspection system that can be used by operators with minimal training. Commercially available hardware that has been used to date consists of an electronic controller, several linear probes, and a data-acquisition system.
- Deliver a fully integrated system suitable for deployment and testing in a production environment.
- Develop signal postprocessing algorithms.
- Demonstrate the system's ability to characterize welds with sufficient accuracy and repeatability, and integrate components into a portable system rugged enough for use in a production facility.
- Investigate coupling techniques that would allow existing probes, designed to be used in a water tank, to be used without having to immerse test specimens. A user interface will be required for plant deployment.

Accomplishments

- Evaluated the performance and limitations of existing ultrasonic phased-array systems.
- Conducted a series of laboratory experiments to evaluate the performance of 5-, 10- and 17-MHz phased-array probes for characterization of spot welds in galvanized steel.
- Developed signal-processing algorithms to distinguish between satisfactory, undersized, and defective welds.

Future Direction

- Conduct laboratory experiments to demonstrate the ability of phased-array systems to inspect spot welds with sufficient accuracy and repeatability for the full range of materials and joint configurations used in production.
- Develop automated classifiers to determine weld dimensions and identify defective welds, including cold welds.
- Identify and test coupling techniques that will allow existing probes to be used outside of a water tank.
- Develop a user interface in conjunction with end users to ensure ease of use and reporting of data in the most useful format for inspectors, welding engineers, and plant managers.
- Develop a fully integrated prototype system suitable for deployment and testing in a manufacturing plant.
- Perform large-scale testing and measurement system analysis.

Introduction

Lawrence Berkley National Laboratory (LBNL) previously evaluated the adequacy of commercially available ultrasonic systems for the inspection of spot welds. Although these systems are widely used in European automotive plants, they have not gained widespread acceptance in the United States for a myriad of reasons, including their dependence on trained operators to set system variables and the need to change probes frequently because of the wide range of materials and sheet thicknesses used in production vehicles. Plant managers emphasize the need for intuitive user interfaces and summary reports that can be customized for welding engineers and other plant personnel.

An impediment to implementing new approaches and technology that would advance the state of the art and enable non-destructive spot-weld inspection has been the difficulty of achieving consensus among industry partners on a technology and methodology of choice. LBNL strongly believes that a better approach is to develop platforms that add value immediately, minimize barriers to incorporating emerging technologies at a later date, and are as modular as possible so that they can be easily modified or adapted for new applications. Consistent with that model, the proposed work is to develop a prototype spot-weld inspection platform based on phased-array technology that will be implemented and tested in a manufacturing environment.

Signals from monoprobes, such as those used by the existing commercial systems, are an integrated response over an area, which depends on the diameter of the probe. For these systems, undersized welds and defects are detected by measuring signal amplitudes and comparing them to amplitude gates set by an operator. It has been demonstrated that ultrasonic techniques based only on measurements and evaluation of signal amplitude have poor sizing capabilities. In contrast, a phased-array system allows complex scanning of the acoustic beam through the weld that allows greater accuracy in sizing weld nuggets and provides improved flaw characterization capability.

The current project is making use of an R/D Tech ultrasonic phased-array system loaned to LBNL by the Ford Motor Company. The system consists of an electronic controller, a linear probe, and a data acquisition system. The system is being used to perform laboratory experiments designed to evaluate the performance of existing hardware, determine the optimal probe configuration, and to develop signal-processing and weld-classification algorithms.

A phased array is a multielement piezoelectric device whose elements are individually excited by electronic pulses at programmed delay times. They have several advantages over conventional ultrasonic probes that derive from the ability to dynamically control the acoustic beam transmitted into the structure under examination. An electronic delay can be applied separately to each electronic channel when emitting and receiving the signal. These delay laws permit constructive and destructive interference of the acoustic wavefront transmitted into the structure, allowing predefined ultrasonic beams to be formed.

For the phased-array system commissioned by Ford, a 5-MHz probe was judged to be sufficient to inspect spot-welded sheets for a range of sheet thicknesses between 1.0 and 3.0 mm. An open question at the beginning of the current project was the adequacy of the 5-MHz probe for the full range of materials and sheet thicknesses currently used in production. Phased-array probes are available up to a frequency of 20 MHz. In general, relatively high-frequency probes provide better spatial resolution than lower frequency probes, but are more expensive.

Initial experiments conducted by Ford and R/D Tech were performed in a water tank, which is impractical for manufacturing applications. To make the transition from a laboratory system where samples are immersed in a water tank to a plant deployable system requires developing coupling strategies that ensure good transmission of ultrasonic waves into the part being inspected without being immersed in water. Experiments performed at LBNL demonstrate that a water-filled column confined by a thin membrane provides the necessary coupling to the part when used in conjunction with ultrasonic gel (Figure 1).

Because the welded test specimens are relatively thin, additional space between the probe and the sample is necessary to have an adequate vertical distance for the electronic

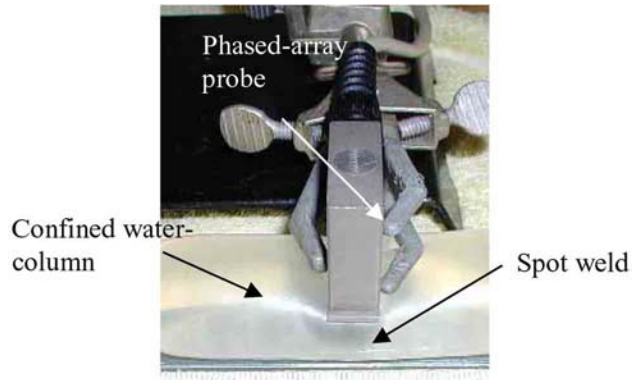


Figure 1. Inspection of spot welds using a phased-array probe with a confined water column for coupling.

beam forming that allows the acoustic energy to be focused at the interface between the sheets.

Initial experiments were performed with a 5-MHz ultrasonic phased-array probe. The results of these experiments indicate that a central frequency of 5 MHz is too low to inspect welds in the thinnest metal sheets used in the automotive industry (thinner than one millimeter). Therefore, a new suite of experiments was carried out with probes with central frequencies of 10 and 17 MHz, and it is the results obtained with these probes that are presented here. The 10-MHz probe is a 32-element linear probe with a 0.4-mm pitch (distance between two successive elements); the 17-MHz is a 128-element focused probe with a focal distance of 12.5 mm and a pitch of 0.28 mm. Experiments were performed in a water tank or using a confined water column with coupling gel between the probe and the sample. The distance between the probe and samples was held constant at 12.5 mm for all experiments to allow the same focal law to be used. For the results presented here, the samples consisted of spot-welded strips made from 1.4-mm-thick galvanized mild-steel sheet metal.

Phased-Array Inspection Strategy

For the work performed to date, electronic scanning and focusing laws were combined to inspect the spot welds. Scanning is performed by electronically translating the ultrasonic beam across the sample by firing a specified number of elements in sequence. Focusing is accomplished by applying symmetrical delay laws to the elements. For experiments performed with the 10-MHz probe, eight elements are used at a time, and the acoustic energy is focused at the interface between the two sheets. The beam is then electronically scanned across the weld in steps of one element; for example, elements 1 through 8 are excited to generate the first signal, elements 2 through 9 generate the second signal, and so forth, with elements 25 through 32 generating the last signal. For one spot weld, this results in a total of 25 independent signals.

Fourier-Based Signal Processing

The 25 signals recorded while scanning through the weld are analyzed in the time and frequency domains. Examples of A-scans and their Fourier transforms are shown in Figure 2 for the beam focused inside [2(*a*) and 2(*b*)] and outside the welded area [2(*c*) and 2(*d*)]. The signals displayed in Figures 2(*a*) and 2(*c*) are the moduli of the analytical signals. Note that the

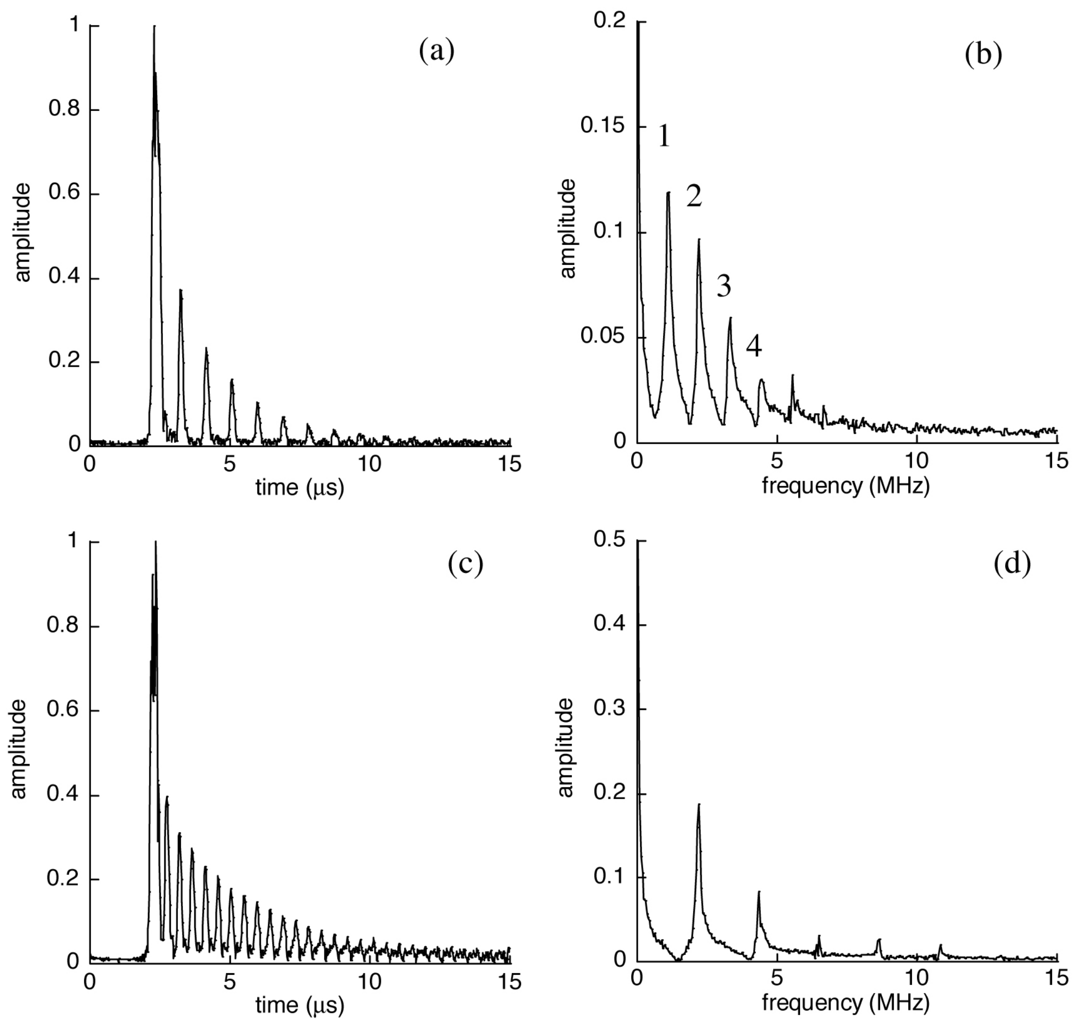


Figure 2. Signal in time recorded with a phased array when the ultrasonic waves are completely transmitted into the second sheet and reflected off the back surface (*a*), compared to signals recorded when waves are totally reflected off the interface between the two sheets (*c*), as occurs outside the welded area, and their respective FFTs [(*b*) and (*d*)].

metallurgical changes in the welded area do not cause a change in acoustic impedance large enough to create a noticeable reflection at the boundary of the weld nugget [see Figure 2(*a*)]. The Fast Fourier Transforms (FFTs) presented here are calculated starting from the first peak after the front-surface echo to minimize the influence of the surface reflection off the top sheet, which does not carry any information about the structure of the weld. The signals in the time domain can be mathematically described as the convolution, $s(t)$, of two functions:

$$s(t) = E(t) \otimes \left[III(t/T)\, e^{-\alpha t} \right] , \qquad (1)$$

where $E(t)$ is the modulus of the ultrasonic reflection; $III(t/T)$ is the Shah function, which is a series of Diracs; $e^{-\alpha t}$ accounts for attenuation; and the symbol $\otimes$ denotes convolution. T is the time interval between the Diracs in the Shah function and is equal to 4d/V for ultrasonic waves propagating into the second sheet, or 2d/V for ultrasonic waves reflected off the interface between the sheets, where d is the thickness of one sheet, and V is the longitudinal velocity in steel. The FFT of $s(t)$, $\tilde{S}(\omega)$, is given by Equation 2:

$$\tilde{S}(\omega) \propto \tilde{E}(\omega) \left[III(\omega T/2\pi) \otimes e^{-(\omega/\alpha)} \right] . \qquad (2)$$

The power spectrum can be described as a succession of peaks with approximately Gaussian decay. Figure 2 shows the signals, $s(t)$ [2(*a*) and 2(*c*)], and the power spectra, $\tilde{S}(\omega)$ [2(*b*) and 2(*d*)], for the two extreme cases of total transmission into the lower sheet and total reflection off the interface between the two sheets, respectively. A first approach to infer weld quality from these data is to identify how many consecutive signals among the 25 are similar to the characteristic signal for total transmission into the lower sheet.

However, fully characterizing the welded area is not as simple as identifying characteristic signals. When scanning at the boundaries of the weld nugget, the source, which is a focused line, begins to be longer than the weld nugget. Because the signal from the linear probe is an integrated response along the line, the signals recorded at the boundary of the weld nugget also contain ultrasonic waves reflected off the interface between the two sheets outside of the welded region; this leads to intermediary peaks in the time domain. The difficulty is in determining the magnitude of these reflections compared to the energy transmitted into the lower sheet through the weld.

As described above, existing techniques using monoprobes distinguish between several weld qualities by setting amplitude thresholds. Classification of the weld depends on whether the amplitude of these intermediary peaks is higher than a threshold set by the operator. This technique works well to a certain extent. However, consider the two signals shown in Figure 3 obtained using a phased array. In both cases, some of the intermediary peaks are higher than the threshold indicated by the horizontal line [3(*a*) and 3(*c*)]. In the first case [3(*a*)], the first intermediary peak has an amplitude higher than the threshold; the following intermediary peaks are quickly attenuated, and their amplitude falls into the noise level. In the second case [3(*c*)], several of the intermediary peaks have amplitudes higher than the threshold. Although these two signals are obviously different in this respect, a classifier based on any intermediary peaks exceeding the threshold would categorize these welds as being the same. This is a problem in general with "hard" classifiers. An alternative approach is to use Fourier analysis. The magnitude of the intermediary peaks is automatically captured in the frequency domain. The higher the energy contained in the intermediary peaks in the time domain, the lower the amplitude of the odd peaks [labeled 1 and 3 in Figure 2(*b*)] in the Fourier domain.

The ratio of the odd peaks to the even peaks is an indication of how much of the total energy is transmitted into the lower sheet.

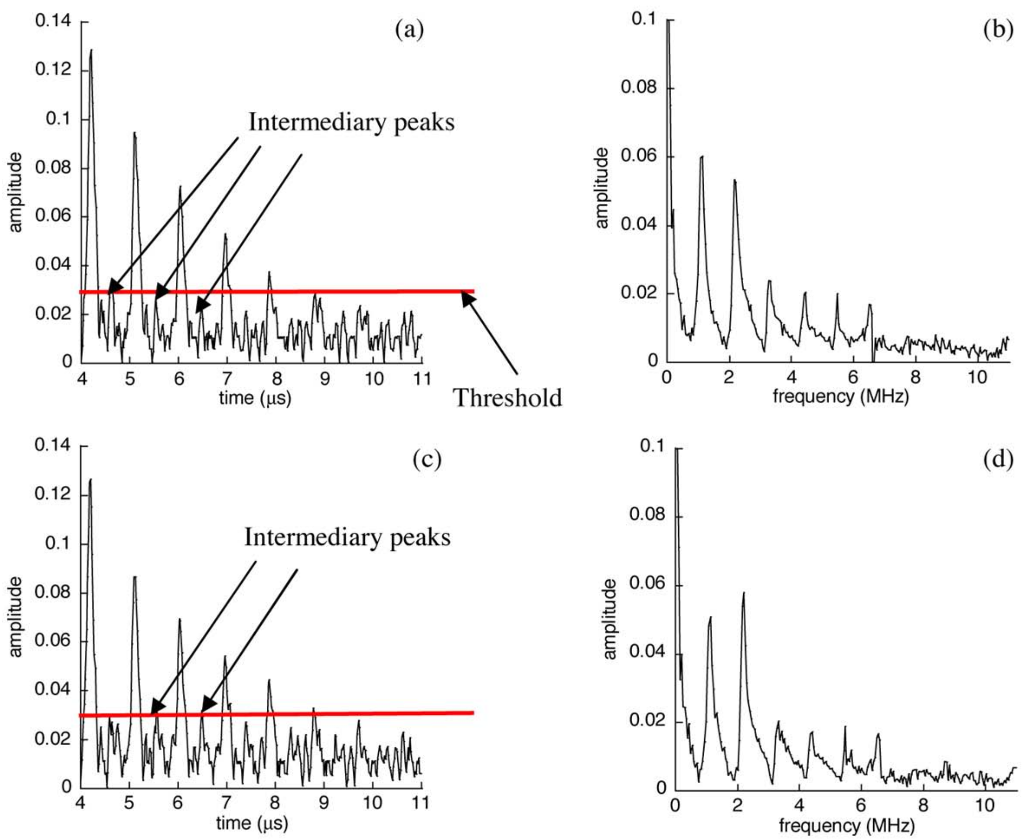


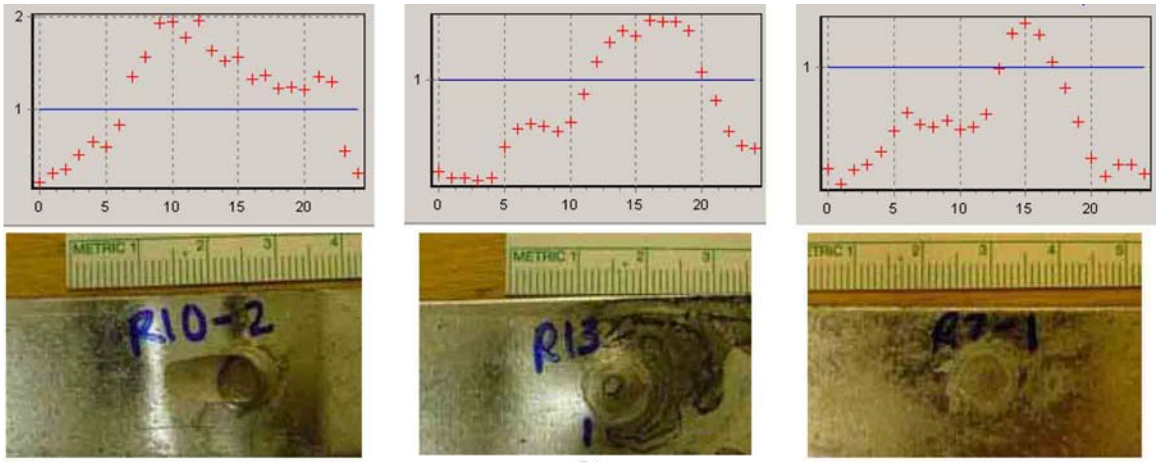
Figure 3. Two phased-array signals recorded when the ultrasonic waves are partially reflected off the interface between the two sheets [(*a*) and (*c*)], and their respective FFTs [(*b*) and (*d*)].

Results Obtained Using A 10-MHz Probe

The industry criterion for evaluating welds is based on the size of the weld button when the welded joint is peeled open. Welds are characterized as undersized when the weld-button diameter is between $2\sqrt{d}$ and $4\sqrt{d}$, and as defective when the diameter is smaller than $2\sqrt{d}$, where d is the thickness of a single sheet. As described above, peak ratios calculated in the Fourier domain are related to the amount of energy transmitted into the second sheet. Peak ratios were calculated for each of the 25 signals that comprise the scans of each weld. The values of the peak ratios, along with pictures of the peeled welds, are shown in Figure 4 for three spot welds with different qualities: satisfactory (a), undersized (b), and defective (c), respectively.

To determine the relationship between characteristic signals and button diameters on peeled samples, the first approach was to estimate the button diameter by counting how many successive signals had peak-ratio values above one, indicative of good transmission into the lower sheet. The distance between two successive signals corresponds approximately to the pitch of the probe, which is 0.4 mm for the 10-MHz probe. Button diameter can thus be estimated by multiplying the number of consecutive signals by the pitch of the probe. For the three welds pictured in Figure 4, the measured and estimated diameters are reported in Table 1.

Comparing the measured and estimated diameters for 150 spot welds indicates that the analysis of peaks in the Fourier domain gives a good indication of the weld quality



(a) (b) (c)

Figure 4. Fourier peak ratios (top row) and pictures of the peeled specimens (bottom row) for a satisfactory weld (*a*), an undersized weld (*b*) and a defective weld with no visible button (*c*).

Table 1. Measured and estimated weld-button diameters using only peak-ratio information

Measured diameter, mm	6.4	3.2	0
Estimated diameter, mm	6.0	2.8	1.2

but does not necessarily give an accurate value of the weld-button diameter. Work under way is focused on developing mathematical algorithms to estimate the size of the weld button from the ultrasonic data.

A challenge in identifying defective welds is that they are often characterized by solid, but weak contact between the two metal sheets that allows transmission of the ultrasonic waves into the lower sheet. This is the case for the cold weld pictured in [Figure 4(*c*)]. Other parameters, such as the ultrasonic-wave attenuation and the depth of the surface indentation, are currently being evaluated to determine if they are diagnostic parameters that can be used to provide additional information useful in defining evaluation criteria. Image-processing techniques are also being investigated.

As discussed in the previous section, one of the limitations of using an unfocused linear probe is that each signal is an integrated response along a line. A way around this problem is to use a focused probe. The experiments discussed above were repeated using a 17-MHz focused probe, and the results are discussed in the following section.

Results Obtained Using A 17-MHz Focused Probe

The experiments performed using the 17-MHz focused probe were made in a water-immersion tank because of the difficulty of coupling the focused probe to the confined water column. The probe is shaped to provide a natural focus at a depth of 12.5 mm. For each measurement, 64 out of 128 elements were used, 16 elements at a time. The elements were focused at the interface between the two sheets. The probe was mechanically scanned in the direction perpendicular to the direction of the electronic scan with a step size of 0.28 mm, which is equal to the pitch of the probe. A total of 3216 A-scans were recorded for each weld in approximately 1 s. The data were processed to measure the Fourier-peak ratios described above, as well as to obtain thickness, indentation, and attenuation measurements. The thickness measurement was made between two back-wall echoes assuming a velocity of 5.9 mm/µs.

Images illustrating the Fourier peak-ratio processing are shown in Figure 5 together with pictures of the weld buttons. The circles superimposed on the Fourier peak-ratio images indicate the measured diameters of the weld buttons. The peak-ratio images [Figures 5(*c*) and 5(*e*)] allow satisfactory and undersized welds to be distinguished according to the size of the area where there is significant transmission of energy into the lower sheet. Although defective welds such as cold welds can result in a large area of ultrasonic transmission into the second sheet, the Fourier peak ratio [Figure 5(*f*)] indicates that the areas of high transmission are relatively sparse and dispersed compared to the well-defined and concentrated areas for the satisfactory and undersized welds.

Other criteria can be used to help distinguish weld quality, such as the indentations on the surface of the sheets caused by the welding electrodes. During the welding process, heat is created at the interface between the electrodes and the metal sheets, leaving indentations on the top and bottom surfaces. The depth of the indentation is

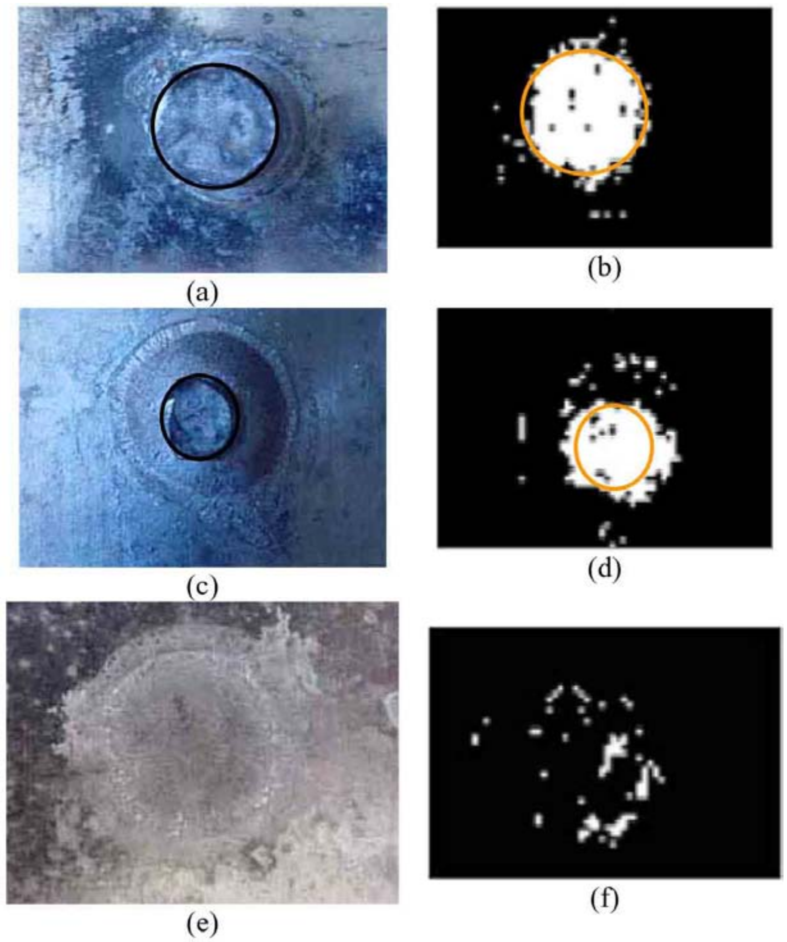


Figure 5. Pictures of the peeled weld buttons (left-hand column) for a satisfactory (*a*), an undersized (*c*) and a cold weld (*e*), and images displaying the Fourier peak ratios (right-hand column) for the same welds (*b*, *d*, *f*). The superimposed black circles on the pictures in the first two rows indicate the measured diameter of the weld button. The same circles are superimposed on the corresponding Fourier peak-ratio images for comparison.

often related to the quality of the weld because it is correlated to the heat created.

A model has been developed to describe the transmissivity of ultrasonic waves through a weld nugget. The model is being used to help understand the relationships between ultrasonic signals and weld quality, which is a necessary step in developing algorithms that will allow automated weld classification based on ultrasonic measurements.

Conclusions

Work to date demonstrates that characterization of spot welds is possible using ultrasonic phased-array technology. Phased arrays have several advantages over monoprobes, including the ability to perform high-resolution scans that greatly increase detection and characterization capabilities. They are also less sensitive to probe placement and provide the ability to inspect a wide array of welds with a single probe. The remaining research challenge is to develop, test, and refine the techniques so that they are suitable for large-scale manufacturing applications. This requires sensor development, integrated real-time diagnostic tools that operate at sufficient speed for assembly-line use, determination of resolution limits and the best diagnostic parameters for specific applications, and demonstration of robustness, accuracy, and cost-effectiveness under realistic operating conditions.

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